Turbulence Intensity as Influenced by Surface Roughness and Mean Velocity in a Wind-Tunnel Boundary Layer

Leon Lyles, Lowell A. Disrud, and R. K. Krauss
MEMBER ASAE ASSOC. MEMBER ASAE

FLUID turbulence is a factor in movement of solids in the atmospheric boundary layer. When forces generated by wind overcome forces of gravity, cohesion, and particle moment about points of contact, soil particles are set in motion (17)*. A wind strong enough to move soil particles is always turbulent (3), i.e., its flow has irregular fluctuations of velocity, which are superimposed on the mean flow.

The importance of fluctuations in velocity and pressure in determining critical (threshold) values that initiate particle movement has been known many years. Kalinske (9) noted that studies concerned only with mean conditions seemed to lack fundamental soundness. Zingg and Chepil (23) advised thorough investigation of turbulence intensity of wind movement in the field.

The level or intensity of turbulence can be described by the quantity $\frac{[1/3(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})]^{1/2}}{\overline{u}_m}$, or, if the turbulence is isotropic, by $\frac{(\overline{u'^2})^{1/2}}{\overline{u}_m}$ (21) where $(\overline{u'})^{1/2}$, $(\overline{v'^2})^{1/2}$, and $(\overline{w'^2})^{1/2}$ are the root-mean-square (RMS) of the fluctuating velocity components in a mutually perpendicular coordinate system (u, v, w), respectively; u is in the direction of the mean fluid flow and w is normal to it. $\overline{u}_m$ is the mean wind speed at some point in space for the flow in question. For convenience, RMS values for the longitudinal component and the vertical component are noted as σ_u and σ_w and the longitudinal and vertical turbulence intensities as T_u and T_w or $\frac{\sigma_u}{\overline{u}}$ and $\frac{\sigma_w}{\overline{u}}$, respectively.

Several workers (5, 6, 8, 14, 19) have suggested or reported that, for neutral (adiabatic) conditions, the ratios of the fluctuating components σ_u, σ_v, and σ_w to the friction velocity, u_*, should be approximately constant in the constant-stress layer. The friction velocity is defined as $(\tau_0/\rho)^{1/2}$ where τ_0 is the shear stress at the surface and ρ is fluid density. Lumley and Panofsky (14) report values of the constant C in $\frac{\sigma_u}{u_*} = C$ as between 2.1 and 2.9 for neutral conditions. Extremes found in other papers were 3.1 (12) and 1.7 (19). Values of the constant A in $\frac{\sigma_w}{u_*} = A$ are less certain. Again, Lumley and Panofsky (14), citing other workers, reported values from 0.7 to 1.33.

Although many researchers have measured turbulence intensity in one or more directions, few have done so explicitly to determine the influence of surface roughness on the magnitude of velocity fluctuations. While it is generally agreed that increasing surface roughness increases longitudinal turbulence intensity of wind-tunnel boundary layer flows, notable exceptions are found in statements by Chepil and Siddoway (2) and in Moore's data (16).

Chepil and Siddoway (2) concluded, after measuring local turbulence intensity $(\sigma_u/\overline{u}_z)$ with a strain-gage anemometer in a wind tunnel, that intensity is not a function of friction velocity or surface roughness. However, their conclusions are not well supported by their data. Moore's data (16) indicate that σ_u/u_∞ is greater for a surface composed of ⅛-in. square bars than of ½-in. square bars, both with spacings of four times height. u_∞ is the free-stream mean velocity.

Reported here are effects of surface roughness and mean windspeed on the longitudinal and vertical velocity fluctuations (RMS values) in the boundary layer of a low-velocity wind tunnel.

TABLE 1. SUMMARY OF DATA FOR ROUGHNESS ELEMENTS

Surface identification	Average diameter, $\overline{d}_p$, mm.	Standard deviation, σ' mm.	Geometric standard deviation, σ_g	Areal density, number per sq cm
S_1	Smooth	....	....	....
S_2	6.06	0.22	1.04	2.87
S_3	16.41	0.62	1.04	0.41
S_4	24.53	0.72	1.03	0.18

Experimental Procedure

The study consisted of three replications of a factorial arrangement of treatments. Two factors were involved, both at four levels:

Factor 1: Surface roughness composed of 0, 6.1, 16.4, and 24.5 mm mean diameter spheres.

Factor 2: Mean windspeeds of 536 (12 mph), 805 (18 mph), 1,073 (24 mph), and 1,341 (30 mph) cm per sec.

The wind tunnel is a recirculating push-type tunnel 60 inches wide, 76 in. high, and 54 ft long. Airflow is generated by a 10-blade, variable-pitch axivane fan, without pressure gradient controls. A slight favorable pressure gradient of 0.00029 in. of water per ft exists at a windspeed of 894 cm per sec (20 mph). Airflow distribution outside the boundary layer is good.

The roughness elements were spherical glass or tapioca particles with narrow distributions (Table 1). The "smooth" surface was a flexible neoprene sheet. Each surface covered the entire upwind length of the tunnel floor. All measurements were 37 ft downstream, assuring equilibrium between the flow and the surface.

Mean windspeeds were measured with pitot-static tubes connected to a sensitive differential pressure transducer and associated recorder. Free-stream velocity (u_∞) was measured near the center of the tunnel and was monitored during all tests.

The RMS of the fluctuating components across the boundary layer was determined from measurements with a constant-current, hot-wire anemometer, sum-and-difference unit, and random

Paper No. 69-701 was presented at the Winter meeting of the American Society of Agricultural Engineers in Chicago, Ill., December 1969, on a program arranged by the Soil and Water Division. Approved as a contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Kansas Agricultural Experiment Station (department of agronomy contribution No. 1116).

The authors are: LEON LYLES, agricultural engineer, LOWELL A. DISRUD, agricultural engineer, research assistant, R. K. KRAUSS, soil scientist, research assistant, U.S. Department of Agriculture, Manhattan, Kansas.

* Numbers in parentheses refer to the appended references.

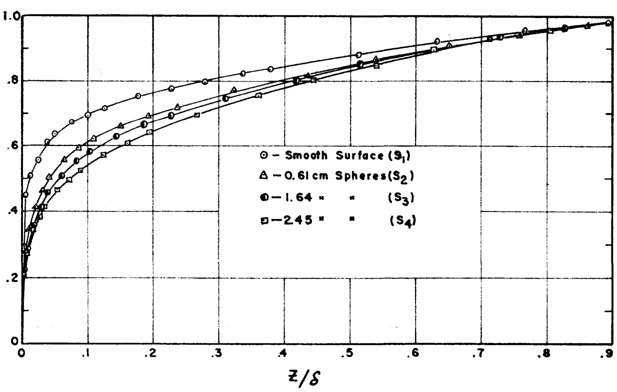

FIG. 1 Turbulent boundary layer profiles on indicated rough and smooth surfaces.

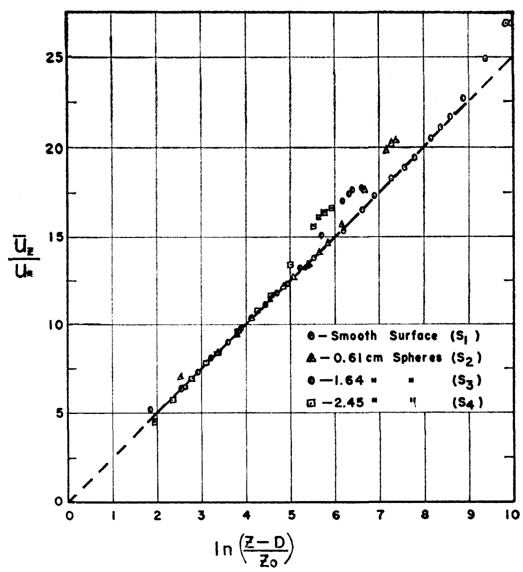

FIG. 2 Logarithmic law for mean velocity over smooth and rough surfaces.

signal voltmeter. A 1,000 or 7,000 Hz, low-pass filter was used to eliminate frequencies above those values.

Air temperature in the tunnel was monitored with thermocouples and a recording potentiometer. Elevations in the boundary layer were set with a vernier staff gage accurate to about 0.3 mm.

Experimental Data and Observations

Before experimental data are presented, comments about corrections are necessary. In highly turbulent flows where fluctuations are not much smaller than the mean velocity, the nonlinearity of a hot-wire anemometer results in large errors (8, 20, 22), which cannot be completely overcome by using linearizing electronic circuits (18).

The magnitude of the turbulence intensity measurements over the rough surfaces near the boundary indicated that corrections must be used. The equation, supplied by manufacturers of the hot-wire equipment, for the most probable error, is:

$$(\epsilon) = \tfrac{1}{2}\left[-\left(\frac{u_2}{C_o} - \frac{u_1}{C_o}\right) + (e_2 - e_1)\frac{dc}{de}\right] \quad \ldots\ldots\ldots\ [1]$$

where u_1 and u_2 are the peak minimum and maximum instantaneous velocities, respectively, with the wire normal to the mean flow direction, e_1 and e_2 are the corresponding voltages, C_o is a wire constant, and $\frac{dc}{de}$ is the slope of the hot-wire voltage versus velocity curve at the mean velocity in question.

We assumed that distribution of the fluctuations was gaussian. For intensity values less than about 10 percent, the errors are insignificant. The equation cannot be used for intensity values larger than 33 percent. Consequently, some measurements had to be rejected.

Because turbulence components influence impact and static pressures measured with a pitot-static tube, mean velocity measurements in turbulent flows should be corrected (7, 8, 22). Scottron (22) has discussed errors in pitot-static or total head tube measurements. However, the form of correction equation to use is open to question. We selected the compromise equation that Scottron suggested:

$$\left(\frac{\bar{u}_z}{u_\infty}\right)_{\text{true}} = \left(\frac{\bar{u}_z}{u_\infty}\right)_{\text{meas.}} (F_p)$$

where

$$F_p = \left\{\sqrt{1 + \left(\frac{u_\infty}{\bar{u}_z}\right)^2_{\text{meas.}} \left[\left(\frac{\sigma_u}{u_\infty}\right)^2 + \tfrac{1}{2}\left(\frac{\sigma_w^2 + \sigma_v^2}{u^2_\infty}\right)\right]}\right\}^{-1} \quad \ldots\ldots\ [2]$$

The equation requires data on turbulence components. Based on data presented by Scottron (22) and Lumley and Panofsky (14), we used the corrected data for σ_u and these values of σ_w and σ_v ($\sigma_w = 0.50\ \sigma_u$, $\sigma_v = 0.64\ \sigma_u$) as functions of σ_u to correct the mean velocity measurements.

Dimensionless mean windspeed profiles across the boundary layer were independent of free-stream velocity, u_∞. Consequently, the four free stream velocities for each surface were averaged (Fig. 1).

Table 2 shows the boundary layer depth (δ) and the mean velocity profile parameters from the well-known logarithmic law in neutral air:

$$\bar{u}_z = \frac{u_*}{k} \ln\left(\frac{Z - D}{Z_o}\right) \quad \ldots\ [3]$$

where $\bar{u}_z$ is mean windspeed at height Z, k is Karman's constant (0.4), D is an effective height used to obtain the zero plane displacement, and Z_o is a roughness parameter. Origin for the height measurements was always the smooth surface. Values for D and Z_o were from a least-squares analysis using measurements in the constant-stress layer.

Local longitudinal turbulence intensity, T_u, for a given height and surface did not depend on mean windspeed (Table 3), so averaging data for a given surface was permissible (Table 4). With a few exceptions, each value in Table 3 is an average of 12 separate hot-wire measurements. In the boundary layer, local intensity increases towards the surface and obviously the longitudinal turbulence intensity increases with increasing roughness in the boundary layer over the range of roughness tested.

Values of "constant" C are given in Tables 5 and 6. Values of C appear to be independent of mean windspeed (Table 5), so data for each surface may be averaged (Table 6). The C values, except those very near the boundary, appear nearly constant over the lower 20 percent of the boundary layer, the constant-stress layer. They obviously are not constant and are not expected to be over the upper 80 percent. The trend to higher C values at greater heights, as roughness increases, is due to the increase in boundary-layer depth and depth of the corresponding constant-stress layer. We found no definite roughness effect on C.

TABLE 2. EFFECTIVE HEIGHT (D), ROUGHNESS PARAMETER (Z_0), AND BOUNDARY LAYER DEPTH (δ) FOR FOUR SURFACES

Surface	Average diameter, $\bar{d}_p$	Boundary layer depth, δ	Effective height, D	Roughness parameter, Z_0
	cm.			
S_1	Smooth	24.1	−0.0129	0.00126
S_2	0.606	28.3	0.6716	0.01886
S_3	1.641	29.5	1.6251	0.04988
S_4	2.453	34.3	2.0582	0.09880

TABLE 3. LONGITUDINAL TURBULENCE INTENSITY (T_u) IN RELATION TO HEIGHT OF MEASUREMENT AND FREE-STREAM VELOCITY (u_∞) OVER 6.06 mm SPHERES, AVERAGE OF THREE REPLICATIONS ($T_u = \sigma_u/\bar{u}_z$)

Height, cm	Longitudinal turbulence intensity (T_u), u_∞ in cm/sec: 536	805	1,073	1,341	Average
	Percent				
36.58	1.8	1.7	1.7	1.7	1.7
24.38	4.2	4.8	4.9	5.0	4.7
15.24	9.9	9.9	10.1	10.2	10.0
9.14	13.9	13.5	13.4	13.5	13.6
5.49	16.5	16.5	16.5	16.4	16.5
3.05	19.3	19.6	19.0	19.1	19.2
1.83	21.7	22.2	22.1	21.5	21.9
1.22	22.6	23.4	23.6	22.4	23.0
0.91	24.0	23.7	24.2	*	24.0
0.61	24.5	25.7	25.6	*	25.2
0.31	26.3	26.2	26.0	*	26.2

* Values rejected because corrections were not acceptable.

TABLE 4. AVERAGE LONGITUDINAL TURBULENCE INTENSITY (T_u) FOR FOUR SURFACES IN RELATION TO HEIGHT OF MEASUREMENT

Height, cm	Average longitudinal turbulence intensity (T_u): S_1	S_2	S_3	S_4
	Percent			
36.58	1.7	1.7	1.9	2.2
24.38	2.3	4.7	6.6	8.2
15.24	5.8	10.0	12.1	13.9
9.14	8.0	13.6	16.2	18.7
5.49	9.6	16.5	19.8	23.4
3.05	11.3	19.2	23.8	27.2
1.83	12.4	21.9	26.3	28.2
1.22	13.2	23.0	27.6	*
0.91	13.8	24.0	29.2	*
0.61	14.4	25.2	*	*
0.31	15.6	26.2	*	*

* Measured values too high to apply corrections.

TABLE 5. VALUES OF CONSTANT C = σ_u/u_* FOR SMOOTH SURFACE IN RELATION TO HEIGHT OF MEASUREMENT AND FREESTREAM VELOCITY (u_∞)

Height, cm	Computed C values, u_∞ in cm per sec: 536	805	1,073	1,341	Average
36.58	0.47	0.43	0.45	0.45	0.4
24.38	0.60	0.60	0.61	0.63	0.6
15.24	1.48	1.46	1.43	1.39	1.4
9.14	1.88	1.85	1.80	1.72	1.8
5.49	2.11	2.07	1.95	1.96	2.0
3.05	2.30	2.23	2.19	2.10	2.2
1.83	2.37	2.31	2.23	2.18	2.3
1.22	2.36	2.28	2.23	2.24	2.3
0.91	2.39	2.28	2.23	2.24	2.3
0.61	2.33	2.24	2.17	2.13	2.2
0.31	2.37	2.16	2.07	2.00	2.2

TABLE 6. AVERAGE COMPUTED C VALUES FOR FOUR SURFACES IN RELATION TO HEIGHT OF MEASUREMENT

Height, cm	Average computed C values: S_1	S_2	S_3	S_4	Average
36.58	0.4	0.4	0.3	0.4	0.4
24.38	0.6	0.9	1.1	1.3	1.0
15.24	1.4	1.8	1.8	1.9	1.7
9.14	1.8	2.1	2.1	2.2	2.0
5.49	2.0	2.3	2.3	2.4	2.2
3.05	2.2	2.4	2.3	2.3	2.3
1.83	2.3	2.5	2.4	2.2	2.4
1.22	2.3	2.4	2.2	*	2.3
0.91	2.3	2.3	2.1	*	2.2
0.61	2.2	2.1	*	*	2.2
0.31	2.2	*	*	*	2.2

* Values of σ_u not acceptable.

The vertical turbulence intensity, T_w, and longitudinal intensity followed similar trends, increasing with roughness and as the surface was approached (Table 7). Values of the "constant" A relating σ_w and u_* also are given in Table 7. The values appear nearly constant over an interior portion of the boundary layer, somewhat deeper than the constant-stress layer. Again no definite roughness effect on A was noted.

Interpretations and Discussion

Very precise measurements of mean velocity and elevation are needed to determine accurately the effective height, D, and the roughness parameter, Z_0. Slight errors in either or including points outside the constant-stress layer can double Z_0. The effective height for surface No. 2 is slightly large compared with the other surfaces, whose values were all less than the mean diameter of the roughness elements.

In neutral air, mean-velocity profiles can be reduced to a single curve by the logarithmic law expressed in equation [3] (Fig. 2). However, consistent with most wind-tunnel measurements, equation [3] is valid only over the lower 15 to 20 percent of the boundary layer. Also, for wind-tunnel measurements the velocity-defect law,

$$\frac{u_\infty - \bar{u}_z}{u_*} = -\frac{1}{k} \ln \left(\frac{Z-D}{\delta}\right) + B \quad \ldots\ldots\ldots\ldots\ldots\ldots [4]$$

appears valid for both smooth and rough surfaces (Fig. 3). B is a constant; the other terms were defined earlier. The average value of B was 2.16 here, slightly lower than the 2.35 reported by Chowdhury (4) over a flat plate. Omitting surface 3, whose values are slightly lower than the other three surfaces, a B value of 2.28 is obtained. The velocity-defect law has little application to atmospheric flows because u_∞ and δ are generally unknown.

The constant longitudinal-turbulence intensity for a given roughness and elevation, regardless of mean wind speed, is due to the strong linear relationship and direct proportionality between the two defining variables, $\bar{u}_z$ and σ_u (Fig. 4). Controlling factors in determining the magnitude of the longitudinal velocity fluctuations at a given elevation were free-stream velocity and nature of the surface (roughness). Roughness exerts more influence on σ_u than expected, e.g., the maximum value of σ_u over the smooth surface at a freestream velocity of 1,322 cm per sec was equaled at a freestream velocity of 780 cm per sec over the roughest surface. Assuming the velocity fluctuations are normally

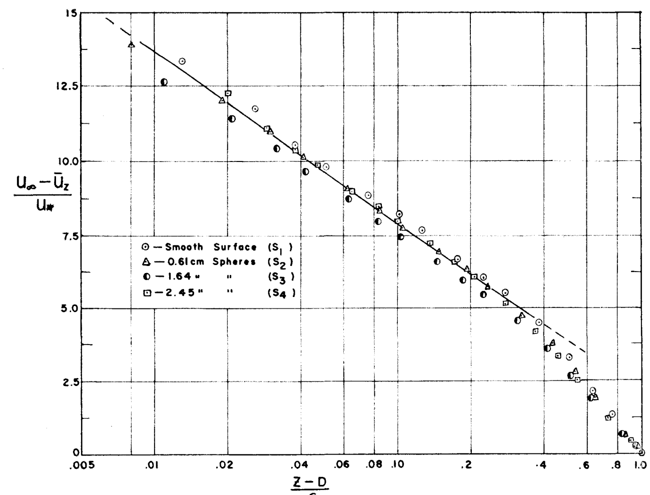

FIG. 3 Velocity-defect law over smooth and rough surfaces.

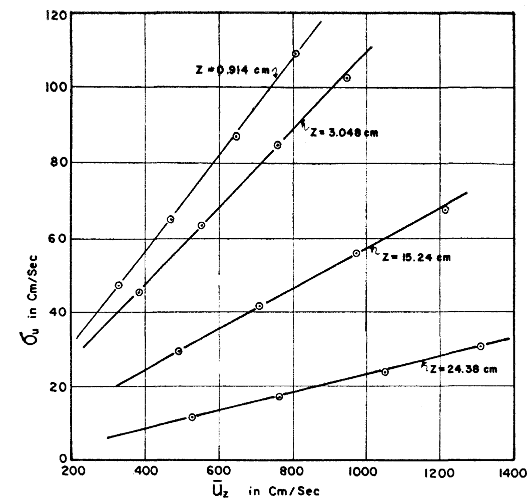

FIG. 4 Relationship between the root-mean-square velocity and the local mean velocity at various elevations above a smooth surface.

distributed, instantaneous velocities at 1.8 cm above the roughest surface could exceed the mean velocity at that height by 85 percent.

Values of C computed from the wind-tunnel data in the constant-stress layer fall in the range of 2.1 to 2.9 given by Lumley and Panofsky (14). The best average value for C from our measurements appears to be about 2.25 ± 0.1, which agrees closely with Monin's (15) 2.3 for neutral atmospheric flow and with Laufer's (13) 2.2 for pipe flow.

We believe that good estimates of σ_u, independent of roughness, can be obtained from direct shear-stress measurements or from accurate mean windspeed profiles using 2.25 for C. Furthermore, C should have considerable utility as a check on measurements of σ_u and on mean windspeed profiles, if good σ_u measurements are available. For example, data of Kawatani and Meroney (10) 8 to 9 meters downstream above various arrangements of 9-cm. pegs in a wind tunnel can be used to compute C values of 0.7 to 0.9 in the constant-stress layer. Consequently, the data are suspect. Checks on their data show that the logarithmic law was used to fit mean velocity data over the upper portion of the boundary layer. That made computed values of u_* two to three times too large.

Vertical turbulence intensity values (T_w) are less certain than the longitudinal ones. One has several opportunities to err in measuring the vertical component. An X probe must be used. Its array constant and half angle are needed to orientate the probe and to calculate T_w. Both the half angle and the X-array constant are difficult to determine precisely.

We used the same correction procedures as for the longitudinal component even though how to judge the accuracy of the sum and difference of the two wire signals is unknown. We believe that values near the boundary in the constant-stress layer are slightly high. Because shorter wires were used for measurements over surface 2 (which reduces the need for corrections), T_w values over that surface are thought to be more nearly accurate than T_w values over the other three surfaces.

A major uncertainty exists in the value of the constant A relating the RMS of the vertical motion, σ_w, and the friction velocity, u_*. Russian workers have reported values from 0.7 to 0.87 and Western workers from 1.25 to 1.33 for neutral air. Some pipe flow and wind-tunnel data indicate the value is about 1.05 (11, 13). Although the data vary some, we obtained, for the lower portion of the boundary layer, average A values of 1.32, 1.04, 1.24, and 1.28 for S_1, S_2, S_3, and S_4, respectively, and 1.22 for the four surfaces tested. Those values more nearly agree with those of Western workers. The 1.04 values for surface 2 is thought to be more nearly accurate; it is almost identical to the 1.05 value Lumley and Panofsky (14) suggested as the best compromise.

TABLE 7. AVERAGE VERTICAL TURBULENCE INTENSITY (T_w) AND COMPUTED A VALUES FOR FOUR SURFACES IN RELATION TO HEIGHT OF MEASUREMENTS

Height, cm	Average vertical turbulence intensity (T_w), percent				Average computed A values			
	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4
30.48	1.4	1.9	2.9	3.8	0.4	0.4	0.5	0.6
15.24	4.9	6.1	8.2	9.9	1.2	1.1	1.2	1.3
9.14	6.2	7.8	10.0	12.2	1.4	1.2	1.3	1.4
3.05	7.3	8.2	13.4	16.0	1.4	1.0	1.4	1.4
1.22	7.7	9.5	14.9	16.7	1.3	1.0	1.2	1.2
0.85	7.5	10.4	16.5	17.1	1.3	0.9	1.1	1.1

Roughening the surface is a cardinal principle in controlling soil movement by wind. Roughness lowers mean windspeed near the surface and shelters erodible grains. However, our data reveal that increasing surface roughness increases velocity fluctuations in both vertical and mean flow directions. That means that some of the benefits gained by roughening are lost by increased turbulence generated by the roughness. For example, the ratio of rough-to-smooth-surface mean windspeed near the surface for equal free-stream velocities was about 0.7 but the instantaneous velocity ratio was about 0.9.

A major effect of turbulent fluctuations in soil erosion would be lowering critical or threshold velocities that initiate particle movement. Using a strain-gage anemometer and a small sphere suspended slightly above surrounding particles, Chepil (1) determined a turbulence factor, T, which he defined as

$$T = \frac{\bar{P} + 3\sigma_p}{\bar{P}}$$

where $\bar{P}$ is the mean pressure and σ_p is the RMS of the pressure fluctuations. He suggested an average value of 2.5 for T and included the turbulence factor in an equation for the threshold or critical drag (τ_c) for erosive-size particles, i.e., $\tau_c = f(\frac{1}{T})$.

A similar approach could be used for the velocity fluctuations:

$$T = \left[1 + 3\left(\frac{\sigma_u}{\bar{u}_z}\right) \right]^2 \quad . \; . \; . \; . \quad [5]$$

Because $\sigma_u/\bar{u}_z$ is a function of surface roughness, T could not be a constant but would increase with increasing roughness. Using $\sigma_u/\overline{u}_z$ values at 0.3 cm above the surface (the lowest elevation measured), T values for S_1, S_2, S_3, and S_4 were 2.16, 3.19, 4.81, and 5.23, respectively. The last two values were obtained by extrapolation. Apparently Chepil's T values would only apply to smooth beds composed of erodible particles.

The single parameter that seems to characterize both the mean and turbulent adiabatic flow field over the interior portion of the boundary layer is the friction velocity, u_*.

Summary

The effects of surface roughness and mean windspeed on the root-mean-square (standard deviation) of the fluctuating velocity components, u and w, in the boundary layer of a low-velocity wind tunnel where studied.

In the lower 15 to 25 percent of the boundary layer, except at the immediate surface, the mean windspeed profile for both smooth and rough surfaces can be described by the well-known equation for adiabatic flow:

$$\frac{\overline{u}_z}{u_*} = \frac{1}{k} \ln \left(\frac{Z - D}{Z_0}\right)$$

where u_* is the friction velocity, k is Karman's constant, D is an effective height, and Z_0 is the roughness parameter, or by the velocity-defect law:

$$\frac{u_\infty - \overline{u}_z}{u_*} = -\frac{1}{k} \ln \left(\frac{Z - D}{\delta}\right) + B$$

where δ is the boundary layer depth, u_∞ is the freestream velocity, and B is a constant of about 2.16 for the data reported.

Both the longitudinal and vertical turbulence intensities for a given elevation and surface roughness were constant regardless of mean windspeed. Both components increase with increasing roughness. Assuming that fluctuations are normally distributed, instantaneous velocities at 1.8 cm above the roughest surface could exceed the mean velocity by 85 percent.

Wind-tunnel data indicate that the constants in the equations, $\sigma_u = Cu_*$ and $\sigma_w = Au_*$, in the constant-stress layer for neutral stability are independent of roughness. σ_u and σ_w are the standard deviations (RMS) of the longitudinal and vertical fluctuations, respectively, and u_* is the friction velocity. The best average value for C was 2.25, which agrees very closely with Monin's (15) and Laufer's (13) values. Some practical uses of C are suggested. The computed A values more nearly agree with those reported by Western workers than with lower values reported by Russian workers.

A turbulence factor, T, which can be used to determine threshold values for soil movement, agrees with Chepil's (1) data (with some restrictions).

References

1 Chepil, W. S. Equilibrium of soil grains at the threshold of movement by wind. Soil Sci. Soc. Amer. Proc. 23:(6)422-428, 1959.

2 Chepil, W. S., and Siddoway, F. H. Strain-gage anemometer for analyzing various characteristics of wind turbulence. Jour. Meteor. 16:(4) 411-418, 1959.

3 Chepil, W. S., and Woodruff, N. P. The physics of wind erosion and its control. Advances in Agron. 15:211-302, 1963.

4 Chowdhury, S. Turbulent eddies in boundary layers on smooth and rough flat plate. M.S. thesis, Civil Engineering Dept., Colorado State Univ., 1966.

5 Corrsin, S., and Kistler, A. L. The free-stream boundaries of turbulent flows. NACA Rpt. 1244, 1955.

6 Davenport, A. G. The spectrum of horizontal gustiness near the ground in high winds. Quart. Jour. Royal Meteor. Soc. 87:(372)194-211, 1961.

7 Davies, P. O. A. L. The behaviour of a pitot tube in transverse shear. Jour. Fluid Mechanics 3:(5)441-456, 1958.

8 Hinze, J. O. Turbulence. McGraw-Hill Book Co., New York, 586 pp., 1959.

9 Kalinske, A. A. Turbulence and the transport of sand and silt by wind. Annals New York Acad. Sci. 44:41-54, 1943.

10 Kawatani, T., and Meroney, R. N. The structure of canopy flow field. Tech. Rpt., Fluid Dynamics and Diffusion Lab, Colorado State Univ., August, 1968.

11 Klebanoff, P. S. Characteristics of turbulence in a boundary layer with zero pressure gradient. NACA Rpt. 1247, 1955.

12 Klug, W. Diabatic influence on turbulent wind fluctuations. Quart. Jour. Royal Meteor. Soc. 91:(388)215-217, 1965.

13 Laufer, J. The structure of turbulence in fully developed pipe flow. NACA Rpt. 1174, 1955.

14 Lumley, J. L., and Panofsky, H. A. The structure of atmospheric turbulence. Interscience Publishers, New York, 231 pp., 1964.

15 Monin, A. S. Empirical data on turbulence in the surface layer of the atmosphere. Jour. Geophys. Res. 67:(8)3103-3109, 1962.

16 Moore, W. L. An experimental investigation of the boundary layer development along a rough surface. Ph.D. dissertation, Univ. of Iowa, 1951.

17 Owen, P. R. Saltation of uniform grains in air. Jour. Fluid Mechanics 20:(2)225-242, 1964.

18 Parthasarathy, S. P., and Tritton, D. J. Impossibility of linearizing a hot-wire anemometer for measurements in turbulent flows. AIAA Jour. 1:(5)1210-1211, 1963.

19 Robertson, J. M., and Martin, J. D. Turbulence structure near rough surfaces. AIAA Jour. 4:(12)2242-2245, 1966.

20 Rose, W. G. Some corrections to the linearized response of a constant-temperature hot-wire anemometer operated in a low speed flow. Jour. Applied Mechanics 29:(3)554-558, 1962.

21 Schlichting, H. Boundary Layer Theory. Fourth edition, McGraw-Hill Book Co., New York, 647 pp., 1960.

22 Scottron, V. E. Turbulent boundary layer characteristics over a rough surface in an adverse pressure gradient. Ph.D. dissertation, John Hopkins Univ., 1967.

23 Zingg, A. W., and Chepil, W. S. Aerodynamics of wind erosion. **Agricultural Engineering** 31:(6)279-282, 284, 1950.